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Spatiotemporal patterns of flatfish bycatch in two scallop access areas on Georges Bank

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Abstract

Bycatch is a constraint to the Atlantic sea scallop fishery, the most valuable single-species fishery along the eastern coast of the United States. To characterize trends in the bycatch of three flatfish species, a fishery-independent scallop dredge survey was conducted in two sea scallop access areas (Closed Areas I and II) on Georges Bank from 2011 to 2014. Generalized additive mixed models were used to identify seasonal bycatch hotspots of yellowtail, winter, and windowpane flounder. In all cases, spatially explicit models best fit the data (deviance explained: 47–73%) and provided insight into the spatial distribution underlying the seasonal trends in each area. Modeled catch rates for the three flatfish species suggested localized catches at discrete times of the year. Catches of yellowtail and windowpane flounder were highest in Closed Area II in the fall and winter, respectively. Winter flounder were caught in the highest numbers in Closed Area I during the summer and fall, and were largely absent from catches in Closed Area II. Our results suggest consistent seasonal trends that may help managers identify the optimal times to open the access areas to the scallop fleet in order to reduce flatfish bycatch.

Keywords: catch per unit effort, GAMM, generalized additive mixed models, sea scallop, windowpane flounder, winter flounder, yellowtail flounder

Introduction

The Atlantic sea scallop (*Placopecten magellanicus*) fishery is the most valuable single-species fishery along the eastern coast of the United States (US; van Voorhees, MS 2014). The species is distributed along the northeastern US continental shelf from Cape Hatteras, North Carolina, to Maine, but the bulk of the fishery's effort is concentrated on the productive scallop beds in the Middle Atlantic Bight and on Georges Bank (NEFMC, MS 2014). Since 2004, the resource has been harvested under a rotational area-based management strategy designed to increase the long-term yield and reproductive potential of the stock by identifying and protecting high-density beds of juvenile scallops from fishing mortality (NEFMC, MS 2003). Under the current plan, the fleet is also given limited access to two static closed areas on Georges Bank (Closed Areas I and II, hereafter also referred to as scallop access areas; Fig. 1) that were established in 1994 to protect spawning habitat of depleted groundfish stocks (Murawski *et al.*, 2000). Although this management strategy has resulted in increased scallop yields (NEFSC,

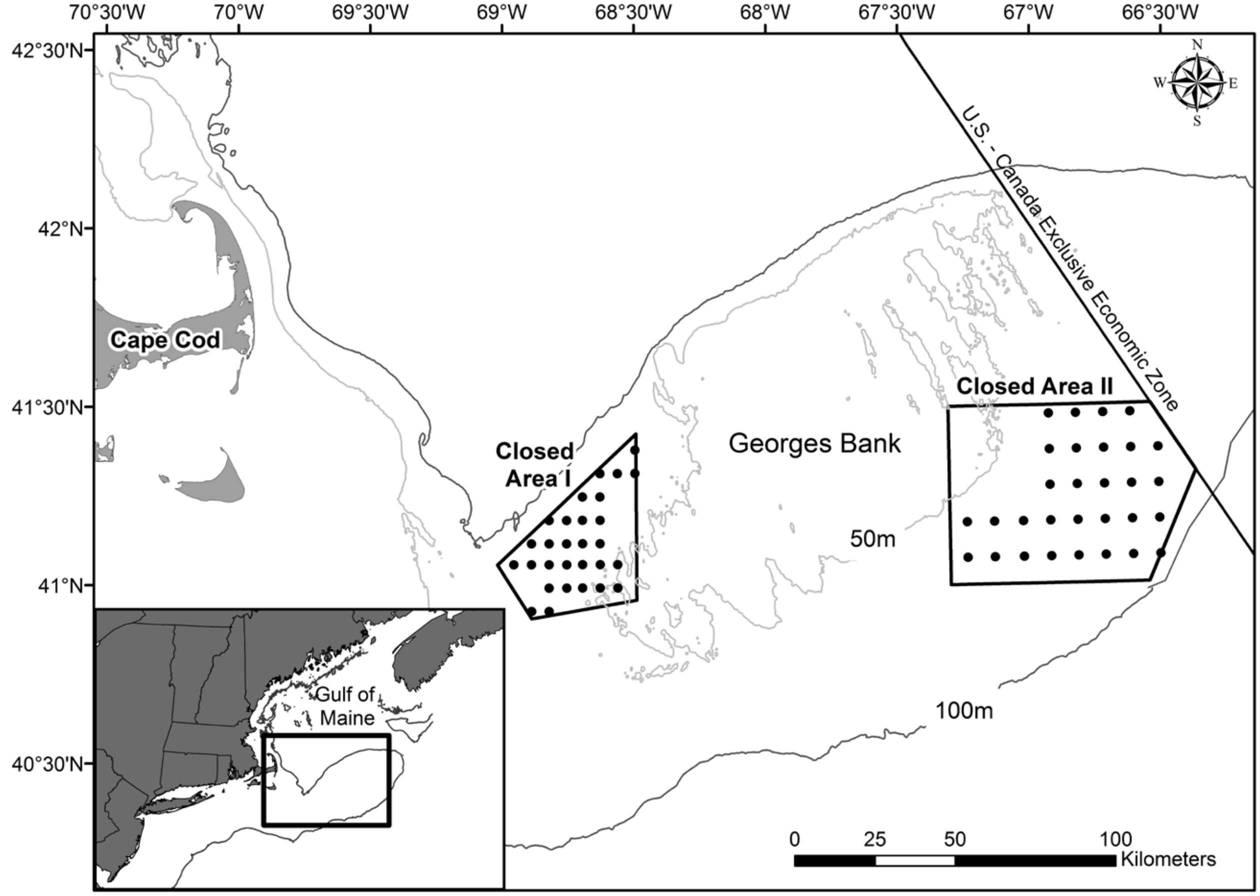

Fig. 1. Location of fixed survey stations in the sea scallop access areas of **Closed Area I** (31 stations) and **Closed Area II** (30 stations) sampled from March 2011 to March 2014.

MS 2010), bycatch of several groundfish species remains a constraint to the fishery, both on Georges Bank and in the mid-Atlantic (O'Keefe and DeCelles, 2013).

In particular, catches of yellowtail flounder (*Limanda ferruginea*) have impacted the timing, location, and, ultimately, the allowable harvest of sea scallops over the past fifteen years (O'Keefe and DeCelles, 2013). The current regulatory framework mandates a strict accounting of fishery-specific bycatch. If the fleet exceeds its annual catch limit for a given species, accountability measures are implemented (*e.g.* in-season closures or quota reductions to account for previous overages; Magnuson-Stevens Fishery Conservation and Management Act; USDOC/NOAA/NMFS, MS 2007). Since 1999, the scallop fleet has been allocated an annual catch limit of Georges Bank yellowtail flounder. Between 1999 and 2009, in-season closures on Georges Bank have occurred several times due to yellowtail overages, resulting in economic losses to the fleet (O'Keefe and DeCelles, 2013). In addition to yellowtail flounder, bycatch of windowpane and winter flounder has also become a management concern in the scallop fishery; an accountability measure for windowpane was recently implemented in the mid-Atlantic (NEFMC, MS 2014). Although accountability measures for flatfish species other than yellowtail are not currently in place for the fishery on Georges Bank, it is plausible they may soon follow.

Given the economic consequences of scallop fishery closures due to yellowtail bycatch (O'Keefe and DeCelles, 2013), numerous efforts to mitigate the fleet's impact on non-target species have been implemented. The fishery funds its own observer program, and has invested heavily in approaches aimed at both reactive (*e.g.* real-time bycatch avoidance; O'Keefe and DeCelles, 2013) and proactive strategies (*e.g.* gear modifications; Davis *et al.*, MS 201 reduce bycatch. However, the current overfished status of the Georges Bank yellowtail flounder stock (TRAC, 2014) and the resulting low annual allocation to the scallop fleet (which was reduced by over 40% in 2014; NEFMC, 2014) means that existing approaches to bycatch reduction may not be sufficient to avoid exceeding catch limits.

Documented seasonal variation in flatfish bycatch rates (Bachman, MS 2009) suggests that targeted time-area closures may be a viable option for the scallop fishery on Georges Bank. Given the relatively stationary nature of scallops (Hart and Chute, 2004) and the migratory patterns of the three flatfish species (Chang *et al*., 1999; Johnson *et al*., 1999; Pereira *et al*., 1999), it is plausible that periods of relative spatial segregation between target and non-target species could be identified based on spatiotemporal patterns in bycatch rates. However, the resolution of the data available is limited. Under the current management strategy, scallop access areas are only open to the fleet during certain periods of designated years, which limits the utility of fishery-dependent data for discerning seasonal trends in bycatch rates. Although the National Marine Fisheries Service-Northeast Fisheries Science Center biannual bottom trawl survey provides a continuous time series of fisheries-independent data for Georges Bank since 1963 (Despres-Patanjo *et al*., 1988), the survey is not conducted at the spatial resolution or temporal frequency required to assess seasonal patterns in flatfish distributions within the access areas.

To collect the fine-scale, fishery-independent information needed to better understand the spatial and temporal dynamics of flatfish bycatch in the sea scallop fishery in Closed Areas I and II on Georges Bank, a seasonal dredge survey was conducted from 2011–2014. Generalized additive mixed models (Wood, 2006, 2011), which provide a flexible framework for the investigation of spatially continuous, non-linear trends (Swartzman *et al*., 1992; Augustin *et al*., 2013), were used to identify spatiotemporal patterns in flatfish bycatch rates. The results are considered in the context of possible time-area management strategies for the Georges Bank scallop access areas.

Materials and Methods

Survey Design

Twenty-nine survey trips were conducted aboard eighteen commercial sea scallop vessels from 2011 to 2014. Survey trips were conducted monthly from March through November of 2011, and every six weeks from January 2012 to March 2014. Sampling locations in Closed Area I and Closed Area II were selected using a fixed station, systematic grid design to ensure uniform spatial coverage of each area (Fig. 1). However, some portions of each closed area could not be sampled due to bottom type (*e.g.* rocky substrate) or high densities of sand dollars (*Echinarachnius parma*). In order to evenly distribute sampling effort to areas with different spatial extents, the distance between stations in each area varied. In Closed Area I (CAI), the 31 stations were separated by 5.4 km east to west and 7.2 km north to south. The 30 stations in Closed Area II (CAII) were separated by 8.6 km east to west and 11.1 km north to south.

On each trip, the vessel was outfitted with two commercial scallop dredges: one standardized 4.6 m wide Turtle Deflector Dredge (TDD) and one 4.6 m wide New Bedford-style dredge, which was supplied by the vessel. Each dredge had 10.2 cm rings and a 25.4 cm mesh twine top, but the TDD had a modified headbale designed to exclude sea turtles (Smolowitz *et al.,* 2012). A more detailed description of the dredges used in this fishery as well as a description of the TDD frame is provided in Smolowitz *et al*. (2012). Only catch data from the standardized TDD used over the entire course of the survey are presented herein. It is important to note that the large mesh used on commercial scallop dredges has a low selectivity for small flatfish (Legault *et al.*, MS 2010). Thus, the flatfish bycatch rates observed during the course of our survey are considered to be representative only of the portion of the population available and vulnerable to capture in commercial scallop dredges.

At each station, standardized survey protocol specified that the vessel operator pass through the center of each grid cell at some point during the tow; tow direction was left to the discretion of the operator. The target tow duration was 30 minutes, with a minimum acceptable tow time of 20 minutes. Tows shorter than 20 minutes or those with gear or other operational issues were deemed invalid, and the station was resampled until an acceptable tow was completed. Target tow speed was 4.8 knots, and dredges were towed with a 3:1 wire to depth scope. Set-out and haul-back coordinates, depth, sea state, vessel speed, and weather conditions were recorded by the vessel operator. Beginning in May 2011, a temperature (Vemco Minilog) and a temperature-depth logger (Star-Oddi DST milli-TD) were attached to the dredge and programmed to acquire data every 30 seconds.

Following each tow, the catch from each dredge was sorted by species. All yellowtail, winter, and windowpane flounder were counted and measured to the nearest cm. Bycatch rates for each flatfish species in each tow were expressed in terms of catch per unit effort (CPUE) as the ratio of the number of fish caught in the TDD and the time of the tow in minutes; CPUE values for tows that varied around the target tow duration of 30 minutes were scaled accordingly.

Seasonal trends in flatfish catches

Generalized additive mixed models (GAMMs; Wood, 2006, 2011) were used to investigate seasonal changes in the spatial distribution of flatfish catches. There were a large number of tows with zero flatfish catch in both areas (Table 1). Therefore, a Tweedie error distribution (which can accommodate continuous data with many zeros; Tweedie, 1984; Dunn and Smyth, 2005) and a log link function were assumed (Candy 2004; Shono 2008). The Tweedie distribution belongs to the family of exponential dispersion models, which generalize the exponential families used in generalized linear and additive modeling frameworks (Jørgensen 1992). The variance of a Tweedie-distributed random variable, Y, is given by $\mathrm{Var}(Y) = \varphi\left[\mathrm{E}(Y)\right]^p$, where φ is a dispersion parameter and p is the Tweedie index parameter, which is a constant. When p is equal to 0, 1, or 2, the Tweedie is equivalent to the normal, Poisson, or gamma distribution, respectively. For values of p between 1 and 2, the model is a compound Poisson-gamma distribution. When p is closer to 1, the Tweedie distribution most closely resembles the Poisson and allows for a point mass at 0; as the value of p increases, the Tweedie more closely approximates the gamma (Candy 2004).

Because we were most interested in describing the spatial distribution of catches over the course of the year, we chose to model catch rates as a function of geographic location and month rather than environmental conditions. Additionally, depth and bottom temperature (the two available environmental variables we expected to correlate most highly with catch rates; Swartzman *et al*., 1992; Hyun *et al*., 2014) were not collected over the entire course of the survey and were highly correlated with longitude and month, respectively. Preliminary analyses also indicated that the results of models based on those covariates did not adequately describe the distribution of residuals; they are therefore not presented further here. For model fitting, tow location was estimated as the midpoint of the great circle distance between the start and end points of each tow using the "geosphere" package (Hijmans *et al*., 2012) in R (R Core Team, 2015). Midpoint coordinates were projected into the universal transverse Mercator coordinate system (UTM zone 19) using the R package "rgdal" (Bivand *et al*., 2013). Although we used standardized sampling protocols on each survey, different vessels were employed over the course of the study. Therefore, vessel was incorporated as a random effect to account for variability due to differences in vessel handling, engine power, or other technical characteristics of the vessels employed, as well as other inter-vessel differences not accounted for by the covariates of interest (Candy 2004; Augustin *et al*., 2013).

The response, the expected CPUE of each flatfish species for tow j from vessel i was modelled as:

$$\log(y_{ij}) = \beta_0 + f_1(\mathrm{month}_{ij}, \mathrm{northing}_{ij}, \mathrm{easting}_{ij}) + \beta_1 * \mathrm{year}_{ij} + v_i + \varepsilon_{ij},$$

where β_0 is an intercept term; f_1 is a smooth function of the covariates associated with vessel i and tow j; northing and easting are projected tow coordinates; β_1 is a coefficient specifying the effect of survey year (note the distinction from calendar year); v_i represents the random effect of vessel; and ε_{ij} is an independently and identically distributed (i.i.d.) error term. It was assumed that $v_i \sim \mathrm{Normal}(0, \sigma_i^2)$ and i.i.d. The incorporation of vessel as a random effect term allows for marginal, "population-level" (*i.e.* vessel-averaged) predictions via integration of v_i out of the conditional CPUE predictions (Candy 2004; Augustin *et al*., 2013).

Table 1. Number of tows capturing zero yellowtail, winter, and windowpane flounder for all survey trips and trips by survey year conducted in two scallop access areas on Georges Bank from March 2011 to March 2014.

Area	Yellowtail	Winter	Windowpane
Closed Area I (*n* = 849)	**517 (61%)**	**428 (50%)**	**227 (27%)**
2011 (*n* = 353)	197 (56%)	191 (54%)	105 (30%)
2012 (n = 248)	150 (61%)	114 (46%)	60 (24%)
2013 (*n* = 248)	170 (69%)	123 (50%)	62 (25%)
Closed Area II (*n* = 857)	**145 (17%)**	**730 (85%)**	**348 (41%)**
2011 (*n* = 379)	52 (14%)	335 (88%)	153 (40%)
2012 (*n* = 238)	49 (21%)	191 (80%)	98 (41%)
2013 (*n* = 240)	44 (18%)	204 (85%)	97 (40%)

Shifts in the spatial distribution of the catch by month are represented by f_l, which is a tensor product interaction of a two-dimensional isotropic smooth for location and a one-dimensional smooth for month. The tensor product construction of this interaction term allows for CPUE to be modeled as a smooth function of location and month while being invariant to their relative scaling (Wood, 2006). Thin plate regression splines (TPRS; Wood, 2006) were used to represent CPUE as a function of geographic coordinates (northing and easting). A cyclic cubic regression spline was used to represent trends in CPUE by month to avoid discontinuities between December and January (Zuur *et al*., 2009). Catches of winter flounder in CAII were too low (Table 2, Fig. 2; observed CPUE < 4.4 fish per tow in all cases; 3rd quantile = 0.0 fish per tow) and diffuse to sensibly model in the framework used, as confirmed by residual diagnostics. Therefore, only the results for winter flounder catches in CAI are presented.

Given that stations in CAI and CAII were separated by approximately 100 km, two unique models were constructed for CAI and CAII to avoid smoothing over areas that were not sampled. Simpler models nested within the above equation (*e.g.* models without month, models with the interaction term between geographic location and month replaced by additive effects; see Tables 3–5 for the full list of models fitted) were also considered. For each species, the Tweedie index parameter (p) was set to the value that maximized the penalized log-likelihood for all model variants (Tables 3–5). All models were fitted via maximum likelihood estimation using the R package "mgcv" (Wood, 2006, 2011).

Model selection and spatial prediction

Model fit was evaluated based on the Akaike Information Criterion (AIC; Akaike, 1973). Interaction and individual

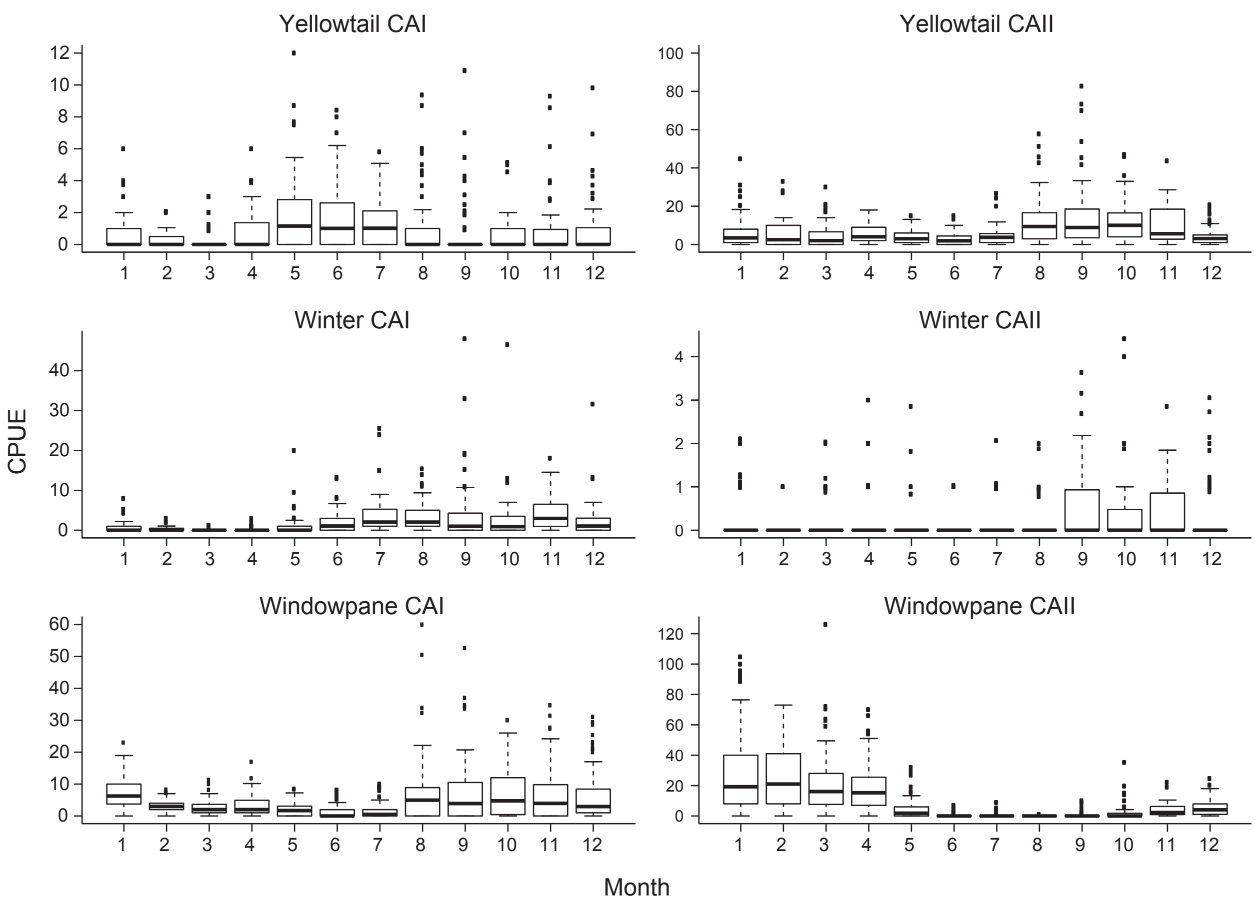

Fig. 2. Catch per unit effort (CPUE; in number of fish per thirty minutes of towing time) of three flounder species in the scallop access areas of **Closed Area I (CAI)** and **II (CAII)** on Georges Bank by month. Note the different axis scales for CPUE in each plot. The axis limits for yellowtail in CAII exclude one large tow in September of 2012 (CPUE = 143 fish per 30 minute tow).

Table 2. Sampling dates, vessel employed, and the median flatfish catch per unit effort (CPUE; expressed as the number of fish caught per half hour) for each survey trip conducted from 2011–2014. The range of CPUE for individual stations within each scallop access area is indicated in parentheses below. **CAI = Closed Area I; CAII = Closed Area II**.

			Yellowtail Flounder CPUE		**Winter Flounder CPUE**		**Windowpane Flounder CPUE**	
Sampling Dates		**Vessel**	**CAI**	**CAII**	**CAI**	**CAII**	**CAI**	**CAII**
2011	3/9 – 3/15	*Arcturus*	0.0 *(0.0 – 3.0)*	4.0 *(0.0 – 21.0)*	0.0 *(0.0 – 1.0)*	0.0 *(0.0 – 2.0)*	2.0 *(0.0 – 7.0)*	10.5 *(0.0 – 126.0)*
	4/14 – 4/20	*Celtic*	0.0 *(0.0 – 2.6)*	5.0 *(0.0 – 18.0)*	0.0 *(0.0 – 2.9)*	0.0 *(0.0 – 2.0)*	1.1 *(0.0 – 5.8)*	10.0 *(0.0 – 34.0)*
	5/11 – 5/17	*Westport*	1.2 *(0.0 – 12.0)*	2.0 *(0.0 – 15.0)*	0.0 *(0.0 – 20.0)*	0.0 *(0.0 – 1.8)*	0.0 *(0.0 – 4.8)*	0.0 *(0.0 – 16.0)*
	6/1 – 6/7	*Liberty*	1.5 *(0.0 – 8.0)*	2.5 *(0.0 – 15.0)*	1.0 *(0.0 – 13.0)*	0.0 *(0.0 – 1.0)*	0.0 *(0.0 – 6.0)*	0.0 *(0.0 – 2.0)*
	7/6 – 7/12	*Endeavor*	1.0 *(0.0 – 5.8)*	2.5 *(0.0 – 20.0)*	1.5 *(0.0 – 24.0)*	0.0 *(0.0 – 0.0)*	1.0 *(0.0 – 10.0)*	0.0 *(0.0 – 5.0)*
	8/15 – 8/21	*Regulus*	0.0 *(0.0 – 6.0)*	12.0 *(0.0 – 57.8)*	2.1 *(0.0 – 15.4)*	0.0 *(0.0 – 2.0)*	2.5 *(0.0 – 20.1)*	0.0 *(0.0 – 1.0)*
	9/10 – 9/16	*Resolution*	0.0 *(0.0 – 4.0)*	10.4 *(2.0 – 70.0)*	2.0 *(0.0 – 48.0)*	0.0 *(0.0 – 1.0)*	1.5 *(0.0 – 37.0)*	0.0 *(0.0 – 0.0)*
	10/4 – 10/10	*Ranger*	0.0 *(0.0 – 5.1)*	16.0 *(3.0 – 47.0)*	2.0 *(0.0 – 46.5)*	0.0 *(0.0 – 4.0)*	4.0 *(0.0 – 26.0)*	1.0 *(0.0 – 15.0)*
	11/29 – 12/5	*Horizon*	1.0 *(0.0 – 9.3)*	4.6 *(0.0 – 20.7)*	1.9 *(0.0 – 18.1)*	0.0 *(0.0 – 1.8)*	3.0 *(0.0 – 23.1)*	3.2 *(0.0 – 15.6)*
2012	1/4 - 1/10	*Wisdom*	1.0 *(0.0 –6.0)*	6.0 *(0.0 – 25.0)*	0.0 *(0.0 – 8.0)*	0.0 *(0.0 – 1.0)*	5.0 *(0.0 – 23.0)*	10.0 *(0.0 – 100.0)*
	2/16 – 2/22	*Venture*	0.0 *(0.0 –2.0)*	2.5 *(0.0 – 33.0)*	0.0 *(0.0 – 3.0)*	0.0 *(0.0 – 1.0)*	3.0 *(0.0 – 7.0)*	21.0 *(0.0 – 73.0)*
	3/10 – 3/16	*Regulus*	0.0 *(0.0 –3.0)*	5.6 *(0.0 – 30.0)*	0.0 *(0.0 – 1.1)*	0.0 *(0.0 – 0.9)*	2.0 *(0.0 – 8.2)*	16.1 *(0.0 – 72.0)*
	4/10 – 4/16	*Endeavor*	1.0 *(0.0 –6.0)*	8.0 *(1.0 – 18.0)*	0.0 *(0.0 – 2.0)*	0.0 *(0.0 – 3.0)*	2.0 *(0.0 – 7.0)*	27.0 *(1.0 – 70.0)*
	5/4 - 5/11	*Zibet*	2.0 *(0.0 –7.7)*	3.7 *(0.0 – 13.1)*	0.0 *(0.0 – 9.5)*	0.0 *(0.0 – 2.9)*	1.9 *(0.0 – 6.0)*	2.9 *(0.0 – 32.0)*
	6/20 – 6/26	*Kayla Rose*	0.9 *(0.0 –8.4)*	1.8 *(0.0 – 10.0)*	1.2 *(0.0 – 8.2)*	0.0 *(0.0 – 1.0)*	0.0 *(0.0 – 7.0)*	0.0 *(0.0 – 4.8)*
	8/6 – 8/14	*Anticipation*	0.0 *(0.0 –9.4)*	7.9 *(0.0 – 45.7)*	2.2 *(0.0 – 9.4)*	0.0 *(0.0 – 1.9)*	3.0 *(0.0 – 33.9)*	0.0 *(0.0 – 0.0)*
	9/25 – 10/1	*Liberty*	0.0 *(0.0 –2.5)*	7.8 *(0.0 – 143.0)*	1.0 *(0.0 – 15.3)*	0.4 *(0.0 – 3.6)*	7.6 *(0.0 – 34.3)*	0.0 *(0.0 – 9.1)*
	11/3 – 11/12	*Horizon*	0.0 *(0.0 –3.9)*	5.6 *(0.0 – 43.6)*	2.8 *(0.0 – 14.5)*	0.0 *(0.0 – 2.9)*	4.8 *(0.0 – 34.7)*	2.3 *(0.0 – 22.2)*
	12/4 - 12/16	*Thor*	0.0 *(0.0 –9.8)*	5.6 *(0.0 – 43.6)*	1.0 *(0.0 – 31.6)*	0.0 *(0.0 – 2.7)*	4.1 *(0.0 – 28.6)*	4.1 *(0.0 – 18.0)*
2013	1/28 – 2/3	*Polaris*	0.0 *(0.0 – 2.1)*	2.0 *(0.0 – 44.7)*	0.0 *(0.0 – 5.3)*	0.0 *(0.0 – 2.0)*	4.0 *(0.0 – 15.0)*	22.7 *(1.0 – 104.7)*
	3/15 – 3/23	*Vanquish*	0.0 *(0.0 – 1.3)*	0.0 *(0.0 – 11.3)*	0.0 *(0.0 – 0.9)*	0.0 *(0.0 – 2.0)*	2.3 *(0.0 – 11.3)*	9.1 *(1.2 – 63.8)*
	4/27 – 5/4	*Endeavor*	0.0 *(0.0 – 3.1)*	3.0 *(0.0 – 10.0)*	0.0 *(0.0 – 1.1)*	0.0 *(0.0 – 2.0)*	3.9 *(0.0 – 17.0)*	11.6 *(0.0 – 31.0)*
	6/12 – 6/19	*Zibet*	1.0 *(0.0 – 6.2)*	1.8 *(0.0 – 7.0)*	1.1 *(0.0 – 13.2)*	0.0 *(0.0 – 1.0)*	1.0 *(0.0 – 8.1)*	0.0 *(0.0 – 7.0)*
	7/26 – 8/2	*Venture*	0.0 *(0.0 – 5.1)*	4.0 *(0.0 – 26.7)*	2.2 *(0.0 – 25.6)*	0.0 *(0.0 – 2.1)*	1.1 *(0.0 – 60.0)*	0.0 *(0.0 – 8.9)*
	9/9 – 9/16	*Atlantic*	0.0 *(0.0 – 10.9)*	5.7 *(0.0 – 41.7)*	1.3 *(0.0 – 10.7)*	0.0 *(0.0 – 3.2)*	4.1 *(0.0 – 52.6)*	0.0 *(0.0 – 10.0)*

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	10/26 – 11/2	*Regulus*	0.0 *(0.0 – 8.6)*	4.4 *(0.0 – 26.4)*	0.8 *(0.0 – 9.0)*	0.0 *(0.0 – 4.4)*	4.0 *(0.0 – 31.4)*	0.0 *(0.0 – 35.2)*
	12/10 – 12/18	*Vanquish*	0.0 *(0.0 – 6.9)*	2.2 *(0.0 – 11.0)*	2.1 *(0.0 – 13.2)*	0.0 *(0.0 – 3.1)*	5.1 *(0.0 – 31.1)*	4.4 *(0.0 – 24.6)*
2014	1/15 – 1/22	*Horizon*	0.0 *(0.0 – 1.2)*	3.2 *(0.0 – 20.4)*	0.0 *(0.0 – 2.2)*	0.0 *(0.0 – 2.1)*	7.6 *(1.2 – 18.9)*	34.1 *(0.0 – 95.6)*
	3/8 – 3/15	*Liberty*	0.0 *(0.0 – 1.0)*	1.9 *(0.0 – 12.0)*	0.0 *(0.0 – 1.3)*	0.0 *(0.0 – 1.0)*	3.0 *(0.0 – 10.0)*	29.2 *(13.3 – 62.9)*

terms were retained in the model if their inclusion resulted in lower AIC values and explained a higher proportion of the deviance. The AIC difference (Δ_i) of each model was calculated based on the lowest observed AIC value (AIC_{min}) as $\Delta_i = AIC_i - AIC_{min}$. Models with $\Delta_i < 2$ were considered indistinguishable in terms of fit (Burnham and Anderson, 2002). Residual plots were examined to assess model fit.

While location and time were included explicitly in the full models, there was still the possibility of unexplained residual correlation. Therefore, model fit was also assessed based on the mean absolute prediction error (MAPE) to corroborate the likelihood-based AIC approach (Augustin *et al*., 2013). Because the CPUE of each species varied widely over the course of the year, we chose to use the MAPE rather than the root mean square predictive error, which is more sensitive to large values (Willmott and Matsuura, 2005). Observed data were split into ten test sets based on randomly sampling fixed station locations. For each test set, models were fitted to the remaining data. Values predicted for the omitted set were then compared to observed values to estimate predictive error. The MAPE for each set was calculated as:

$$MAPE = \frac{\sum_{i=1}^{n} | y_i - \hat{y}_i |}{n} .$$

The ten resulting MAPE values were then averaged to generate an overall MAPE for each model.

The spatially explicit models used herein produce a smooth surface from which the expected flatfish CPUE can be estimated at any location within the study area. For models that included year as a fixed effect, the reference level was set to the last survey year (2013) for prediction. In instances when the best fitting models included geographic coordinates, prediction areas were roughly bounded based on the distribution of tow midpoints to avoid extrapolation into unsampled areas (Augustin *et al*., 1998). The expected flatfish CPUE was predicted over a high resolution grid (10 000 cells in each closed area). As our aim was to identify bycatch hotspots rather than to predict the number of flatfish that would be caught in a given tow, we decided to plot our estimates at this scale to ease interpretation. However, it is important to note that such fine-scale estimates would be prone to bias if used as the basis for field predictions of actual catches.

Results

A total of 1 706 valid tows were completed from March 2011 to March 2014 (Table 2). Over the 29 survey trips, a total of 6 852 yellowtail flounder, 1 754 winter flounder, and 12 202 windowpane flounder were collected in the TDD. Catches of all three flounder species varied substantially between areas and seasons (Table 2; Fig. 2). Yellowtail and windowpane flounder catches were generally higher in CAII, with the greatest number of yellowtail caught in the fall and windowpane in the winter and spring (Fig. 2). Winter flounder catches were generally low throughout the year in both areas, but were highest in CAI in the summer and fall (Fig. 2). Yellowtail CPUE ranged from 0.0 to 12.0 in CAI and 0.0 to 143.0 in CAII. The CPUE of winter flounder and windowpane ranged from 0.0 to 48.0 and from 0.0 to 60.0 in CAI, respectively. In CAII, CPUE of winter flounder ranged from 0.0 to 4.4 and windowpane from 0.0 to 126.0.

Seasonal trends in flatfish catches

The results of the GAMM analyses provided insight into the spatial distribution underlying the monthly trends in flatfish catches for each area. Variation in the CPUE of all three species was best described by models including the month-location smoother, indicating difference in the spatial distribution of flatfish catches by month (Tables 3–5). In all cases, the best fitting models also included survey year as a factor, suggesting differences in the magnitude of catches between years; however, differences in fit between the models including both survey year and the month-location smoother and those only including the month-location smoother were

Table 3. Relative goodness-of-fit for candidate yellowtail flounder catch per unit effort models in scallop access areas in a) **Closed Area I (*n* = 849)** and b) **Closed Area II (*n* = 857**) on Georges Bank. Models are ranked from best to worst fitting. Catch per unit effort was expressed as the number of yellowtail caught per thirty-minute tow. The selected Tweedie index parameter value is also indicated. All models included vessel as a random effect.

a) Tweedie index parameter value = 1.03

Model	*edf*	AIC	Δ_i	Deviance Explained	MAPE
f (month, northing, easting) + year	90.20	1801	0	0.49	0.97
f (month, northing, easting)	87.37	1913	112	0.46	0.96
f (northing, easting) + *f*(month) + year	42.39	2227	426	0.38	1.08
f (northing, easting) + *f*(month)	39.11	2375	574	0.34	1.01
f (northing, easting) + year	35.85	2437	636	0.32	1.06
f (northing, easting)	33.43	2578	777	0.29	1.03
f (month) + year	24.85	3013	1212	0.20	1.14
f (month)	21.36	3206	1405	0.16	1.11
year	19.87	3327	1526	0.14	1.16

b) Tweedie index parameter value = 1.38

Model	*edf*	AIC	Δ_i	Deviance Explained	MAPE
f (month, northing, easting) + year	65.03	4798	0	0.47	4.96
f (month, northing, easting)	66.10	4844	46	0.45	5.09
f (northing, easting) + *f*(month) + year	33.36	4972	174	0.34	5.12
f (northing, easting) + *f*(month)	34.99	4991	193	0.33	5.34
f (northing, easting) + year	33.29	5024	226	0.31	5.96
f (northing, easting)	30.92	5079	281	0.28	5.84
f (month) + year	20.04	5107	309	0.25	5.51
f (month)	21.42	5126	328	0.24	5.67
year	20.20	5161	363	0.22	6.32

Note: northing and easting = tow midpoint coordinates projected into the universal transverse Mercator coordinate system (zone 19); *edf* = total model estimated degrees of freedom; AIC = Akaike information criterion rounded to the nearest whole number; Δ_i = AIC difference rounded to the nearest whole number; MAPE = mean absolute predictive error (in number of fish per 30 minute tow). *f* indicates a smooth function; see text for specifics on the types of smooth functions used for each covariate.

generally minimal (Tables 3–5). Model comparisons based on MAPE estimates supported the model selected based on AIC ranking in all cases (Tables 3–5). In general, the selected models explained a large proportion of the observed variance (deviance explained 0.47 to 0.73 for all cases; Tables 3–5), and residual plots indicated that the assumptions and the selected values of the Tweedie index parameter were appropriate.

For yellowtail, model results for both closed areas suggested changes in the distribution and magnitude of bycatch by month (Fig. 3). In CAI, predicted CPUE was generally low in all months (mean CPUE < 2.0 fish per 30 minute tow for all locations) but was highest along the northwestern boundary from the spring into the fall (Fig. 3a-b). Catches in CAII exhibited greater variation over the year (Fig. 3c-d). The predicted CPUE was relatively low over large portions of CAII, with localized areas of higher catch (CPUE > 15.0) in the eastern portion of CAII during the fall (Fig. 3c-d). Predicted catches in both areas were lower in survey year 2013 than in the previous years (Table 6).

Model results also suggested seasonal changes in the distribution of winter flounder in CAI. Winter flounder were largely absent in predicted catches from February to April (Fig. 4). Predicted catches were highest along the northwestern and southern portions of the area from

July to November (CPUE > 5.0; Fig. 4). The best fitting model suggested that predicted catches in CAI were lower in 2013 than in survey years 2011 and 2012 (Table 6).

Monthly variation in the predicted bycatch of windowpane flounder was greater than for the other two species (Fig. 5). The predicted range of windowpane catches was greater in CAII (CPUE: 0.0–69.9) than CAI (CPUE: 0.0–30.2) but was more episodic in CAII. In CAI, the highest predicted catches occurred in the southeastern portion of the area in the fall (September to December; Fig. 5a-b). The highest predicted catches in CAII occurred from January to April, and were relatively high over almost the entire area surveyed (Fig. 5c-d). From May to August, windowpane bycatch in CAII appeared to be minimal (Fig. 5c-d). Predicted catches in both areas were higher in survey year 2013 than in the previous two survey years (Table 6).

Discussion

The results of our three-year dredge survey revealed considerable spatiotemporal variation in flatfish bycatch both within and between two scallop access areas on Georges Bank. By frequently sampling Closed Areas I and II over an extended period of time, we were able to document localized, seasonal shifts in the bycatch rates of three flatfish species. Our results suggest consistent seasonal patterns in flatfish bycatch that may help managers identify the optimal times to open the access areas to the scallop fleet in order to reduce bycatch of yellowtail, winter, and windowpane flounder.

The selected models for flatfish bycatch explained a high degree of the variability observed over the three years of the survey. This was not surprising given our use of GAMMs, which allow for flexible, non-linear fits to explanatory variables (Wood, 2006).

Additionally, by modeling bycatch rates as a function of location, which is inherently correlated with other factors (*e.g.* depth, bottom temperature, prey availability, substrate type), we were able to encompass a myriad of potential mechanistic drivers without explicitly including them in the model structure. While this certainly compromises a more holistic understanding of the observed trends, as well as the long-term predictive power of the models applied herein, we were most interested in identifying seasonal changes to inform management.

Though we did not directly investigate the effect of environmental factors on bycatch, similar studies conducted in other regions may provide insight into the seasonal trends we characterized. Swartzman *et al*. (1992) used spatially-explicit GAMs to investigate inter-annual trends and environmental effects on flatfish catches from trawl survey data in the Bering Sea. They found that models based only on temperature and depth explained nearly as much of the observed variation in the spatial distribution of

Table 4. Relative goodness-of-fit for candidate winter flounder catch per unit effort models in scallop access areas in **Closed Area I (*n* = 849)** on Georges Bank. Models are ranked from best to worst fitting. Catch per unit effort was expressed as the number of winter flounder caught per thirty-minute tow. The selected Tweedie index parameter value is also indicated. All models included vessel as a random effect.

Tweedie index parameter value = 1.17

Model	***edf***	**AIC**	Δ_i	**Deviance Explained**	**MAPE**
f (month, northing, easting) + year	64.26	2586	0	0.58	1.74
f (month, northing, easting)	63.08	2590	4	0.57	1.76
f (northing, easting) + *f*(month) + year	34.40	3009	423	0.36	2.05
f (northing, easting) + *f*(month)	33.12	3026	440	0.35	2.04
f (month) + year	22.40	3046	460	0.34	2.06
f (month)	21.51	3062	476	0.33	2.04
f (northing, easting) + year	30.92	3429	843	0.17	2.22
f (northing, easting)	29.10	3428	842	0.17	2.21
year	19.75	3460	874	0.15	2.21

Note: northing and easting = tow midpoint coordinates projected into the universal transverse Mercator coordinate system (zone 19); *edf* = total model estimated degrees of freedom; AIC = Akaike information criterion rounded to the nearest whole number; Δ_i = AIC difference rounded to the nearest whole number; MAPE = mean absolute predictive error (in number of fish per 30 minute tow). *f* indicates a smooth function; see text for specifics on the types of smooth functions used for each covariate.

Table 5. Relative goodness-of-fit for candidate windowpane flounder catch per unit effort models in scallop access areas a) **Closed Area I (*n* = 849)** and b) **Closed Area II (*n* = 857)** on Georges Bank. Models are ranked from best to worst fitting. Catch per unit effort was expressed as the number of windowpane flounder caught per thirty-minute tow. The selected Tweedie index parameter value is also indicated. All models included vessel as a random effect.

a) Tweedie index parameter value = 1.22

Model	***edf***	**AIC**	Δ_i	**Deviance Explained**	**MAPE**
f (month, northing, easting) + year	77.00	3787	0	0.61	2.95
f (month, northing, easting)	75.80	3831	44	0.59	2.96
f (northing, easting) + *f*(month)	33.46	4087	300	0.44	3.17
f (northing, easting) + year	32.94	4153	366	0.41	3.55
f (northing, easting)	30.63	4227	440	0.38	3.61
f (northing, easting) + *f*(month) + year	36.60	4444	657	0.48	3.15
f (month) + year	21.77	4487	700	0.26	3.84
f (month)	21.63	4518	731	0.24	3.92
year	19.75	4640	853	0.18	4.17

b) Tweedie index parameter value = 1.37

Model	***edf***	**AIC**	Δ_i	**Deviance Explained**	**MAPE**
f (month, northing, easting) + year	54.40	4067	0	0.73	7.42
f (month, northing, easting)	52.81	4077	10	0.73	7.45
f (northing, easting) + *f*(month) + year	34.22	4278	211	0.62	7.59
f (northing, easting) + *f*(month)	33.54	4280	213	0.62	7.49
f (month) + year	23.02	4356	289	0.57	7.61
f (month)	22.34	4359	292	0.57	7.60
f (northing, easting) + year	27.83	4795	728	0.33	9.68
f (northing, easting)	25.90	4806	739	0.32	9.67
year	20.64	4844	777	0.29	9.90

Note: northing and easting = tow midpoint coordinates projected into the universal transverse Mercator coordinate system (zone 19); *edf* = total model estimated degrees of freedom; AIC = Akaike information criterion; Δ_i = AIC difference; MAPE = mean absolute predictive error (in number of fish per 30 minute tow). *f* indicates a smooth function; see text for specifics on the types of smooth functions used for each covariate.

most species as did the models incorporating geographic coordinates. Limited information is available regarding environmental correlates to flatfish catch rates in CAI and CAII, but temperature and depth likely influence the spatial distribution of yellowtail, winter, and windowpane flounder in a similar fashion (Hyun *et al*., 2014). Habitat type may also be an important factor. Yellowtail and windowpane flounder typically occur on sand or sand-mud substrates (Chang *et al.*, 1999; Johnson *et al.*, 1999), such as those found along the southeastern edge of the access area in CAII (Murawski *et al*., 2000). Winter flounder occupy sandy substrates as well, but are more often associated with the mixed sand-gravel sediments typical of CAI (Pereira *et al*., 1999; Murawski *et al*., 2000).

Alternatively, environmental covariates may operate via indirect effects by modifying the distribution and behavior of prey species, or by influencing the timing of flatfish migration to feeding or spawning grounds (Kotwicki *et al.*, 2005). All three flatfish species are known to make seasonal migrations in response to both abiotic and biotic factors over some portion of their range (Chang *et al*., MS 1999; Johnson *et al*., 1999; Pereira *et al*., 1999). The survey CPUEs of all three species were relatively low during periods of peak spawning on Georges Bank (yellowtail flounder spawn from May to August, winter flounder from March to May, and windowpane from June to October; O'Brien *et al*., 1993), suggesting that neither area serves as a primary spawning ground for the species.

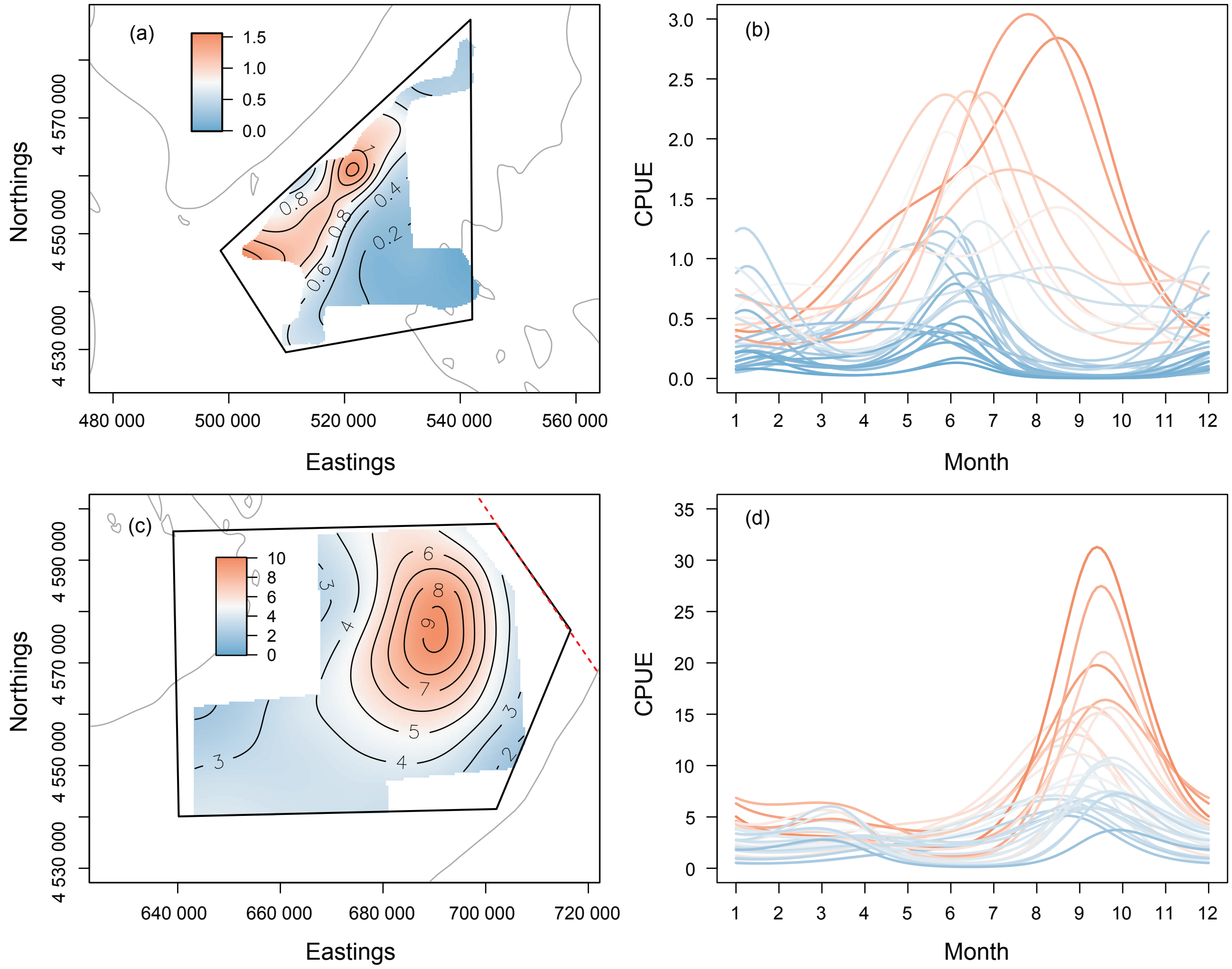

Fig. 3. Predicted mean spatial variation in yellowtail flounder bycatch in **Closed Areas I (a-b)** and **II (c-d)** over the course of the year. The predicted catches at each of the survey stations (31 in **Closed Area 1** and 30 in **Closed Area II**) in each month are also presented to illustrate differences in the timing of peak bycatch within each area (b, d).

The black lines denote the boundaries of the access areas. The red dashed line indicates the boundary between US and Canadian territorial waters. Coordinates are expressed in the universal transverse Mercator coordinate system (zone 19). Note that the panels for each closed area are plotted on different scales for ease of interpretation, but that the color of the annual curves (b) and (d) corresponds to the average catches plotted in (a) and (c).

Maturity data collected during the course of the survey corroborate this, as few flounder were observed to be in spawning condition (C. Huntsberger, unpublished data).

Whatever the driving mechanisms may be, the spatio-temporal patterns of flatfish bycatch documented herein may be useful in terms of optimizing the harvest of sea scallops while avoiding bycatch, and hence accountability measures, in the Atlantic sea scallop fishery on Georges Bank. It is important to note that our results are only suggestive of relative trends in the availability of flatfish species to the scallop fishery, and are not necessarily related to actual trends in abundance in the two areas surveyed, particularly given the potential impact of large tows on estimated trends (Maunder *et al*., 2006). However, our results do suggest that predictable seasonal patterns in flatfish bycatch may provide a practical foundation for the formulation of effective time-area management strategies. Based in part on the survey results reported herein, CAII is now closed to the scallop fleet from August through November (NEFMC, MS 2013) in an effort to reduce high rates of yellowtail bycatch.

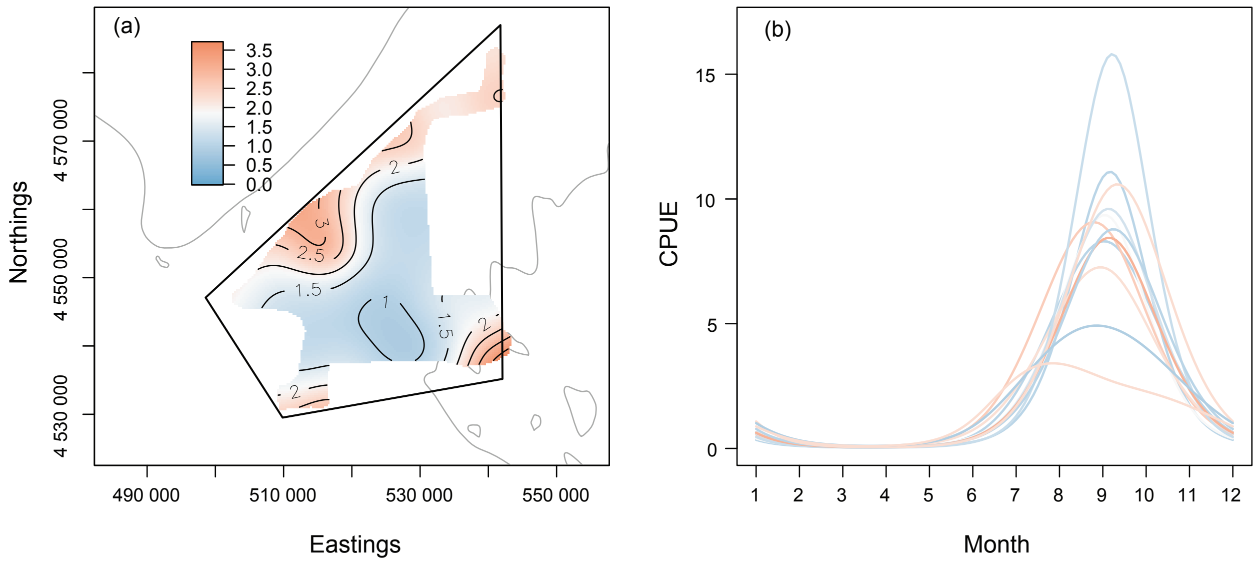

Fig. 4. Predicted mean spatial variation in winter flounder bycatch in **Closed Area I** over the course of the year. The predicted catches at each of the thirty-one survey stations in each month are also presented to illustrate differences in the timing of peak in different areas (b). The black lines denote the boundaries of the access area. Coordinates are expressed in the universal transverse Mercator coordinate system (zone 19). Note that the color of the annual curves (b) corresponds to the average catches plotted in (a).

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Table 6. Parameter estimates for the factor survey year for best-fitting flatfish catch per unit effort in the scallop access areas in **Closed Area I** and **Closed Area II** on Georges Bank.

	Yellowtail		**Winter**		**Windowpane**	
Survey Year	**Value**	**SE**	**Value**	**SE**	**Value**	**SE**
Closed Area I						
2011	-0.40	0.28	-0.03	0.14	0.67	0.095
2012	-0.99	0.25	-0.22	0.16	0.96	0.11
2013	-1.23	0.18	-0.37	0.15	1.22	0.56
Closed Area II						
2011	1.86	0.07	n/a	n/a	-0.00	0.28
2012	1.54	0.10	n/a	n/a	0.15	0.26
2013	1.18	0.10	n/a	n/a	0.40	0.14

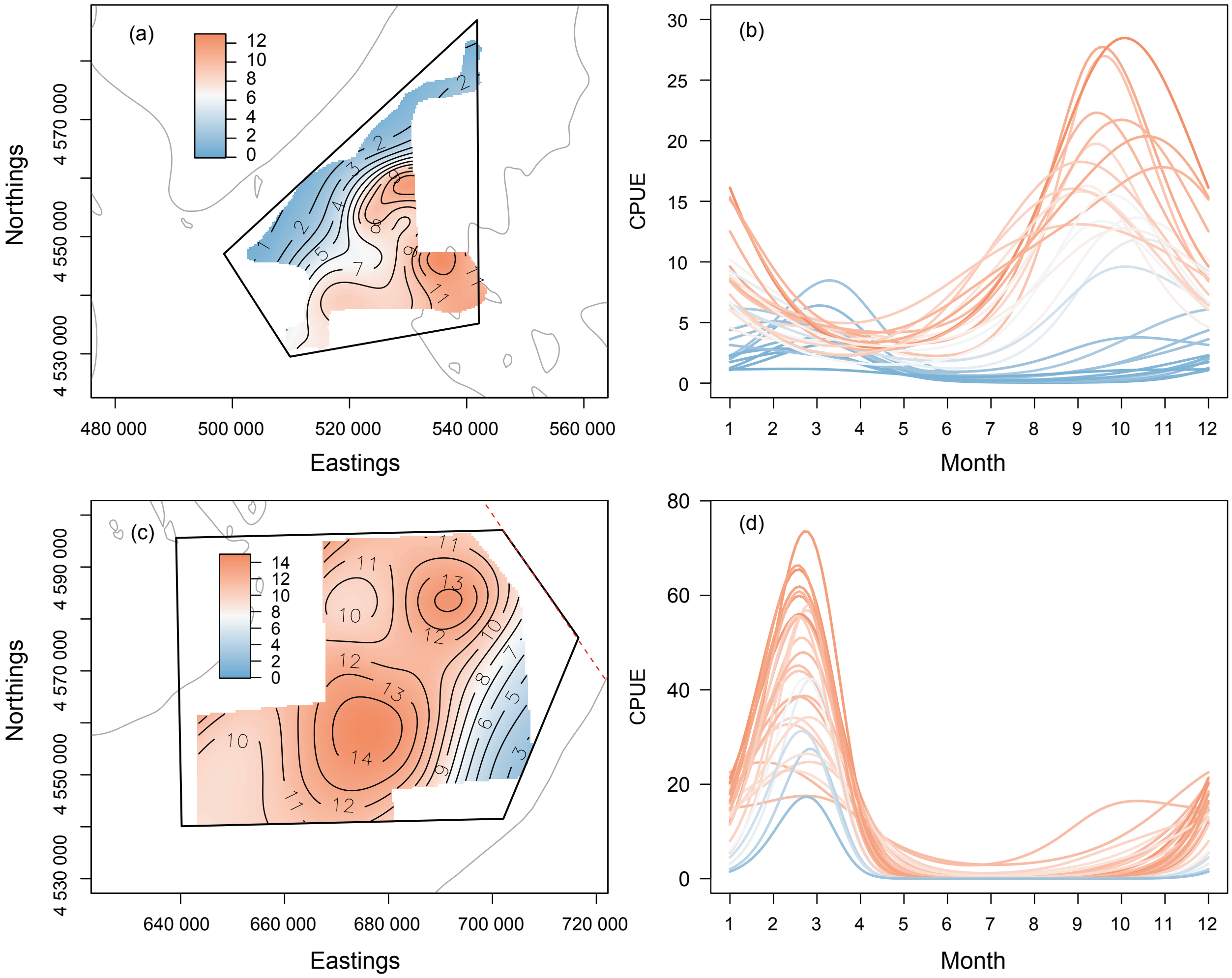

Fig. 5. Predicted mean spatial variation in windowpane flounder bycatch in **Closed Areas I (a-b)** and **II (c-d)** over the course of the year. The predicted catches at each of the survey stations (31 in **Closed Area 1** and 30 in **Closed Area II**) in each month are also presented to illustrate differences in the timing of peak bycatch within each area (b, d).

The black lines denote the boundaries of the access areas. The red dashed line indicates the boundary between US and Canadian territorial waters. Coordinates are expressed in the universal transverse Mercator coordinate system (zone 19). Note that the panels for each closed area are plotted on different scales for ease of interpretation, but that the color of the annual curves (b) and (d) corresponds to the average catches plotted in (a) and (c).

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